Institute of Paper Science and Technology
Atlanta, Georgia

IPST Technical Paper Series Number 665

New On-Line Out-of-Plane Ultrasonic Elastic Stiffness Measurement Technology

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July 1997

Submitted to
1997 TAPPI Process and Product Quality Conference and Trade Fair
Jacksonville, Florida
September 28–October 3, 1997

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NEW ON-LINE OUT-OF-PLANE ULTRASONIC ELASTIC STIFFNESS MEASUREMENT TECHNOLOGY

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ABSTRACT

A new technology for measuring out-of-plane elastic stiffness of paper is introduced. Measurement considerations are described. Recent enhancements to the method of measurement will be introduced which increase the accuracy and robustness of the instrument. The relevance of the instrument to the papermaking process is discussed.

Review

We are pleased to have been recently awarded a U.S. patent (see Fig. 4) titled "System for Measuring the Ultrasonic Velocity in the Thickness Direction of Moving Webs Without Errors Due to Delays in the Onset of Digitization." That patent describes a method for measuring both the ultrasonic transit time and the caliper of a moving web of paper and the subsequent determination of bulk longitudinal velocity (see Fig. 5). As has been shown previously by other researchers, the specific elastic stiffness is equal to the square of that velocity. The specific elastic stiffness multiplied by the apparent density of the sheet is approximately equal to the actual out-of-plane longitudinal elastic stiffness, C_{33}, one of the nine principal stiffnesses necessary to fully characterize the elastic behavior of papers and boards for which mechanical performance is an important converting and end-use parameter.

Briefly, the instrument relies upon short duration ultrasonic waves traveling between two ultrasonic transducers and through two fluid volumes enclosed by two rotating tires, through the tires themselves, and through the moving web. A crosscorrelation integral operating upon pairs of ultrasonic pulses that are generated by all of the acoustical boundaries lying between the two transducer surfaces enables high accuracy ultrasonic time of flight measurements.

That invention is presently in the process of transition to the mill floor where it will occupy a slot in the instrument bay of an ABB Smart Platform™ 1200 scanning frame. Our first full-scale mill trials are scheduled to begin within the year. Two pilot-scale trials have already been conducted. Following the initiation of the patent application process, the instrument has continued to undergo further design refinements, some of which will be described herein.

Synchronization and Tire Nonuniformity

First, in order to attain good measurement accuracy, it has been necessary to average many measurements or make measurements always at fixed angular positions along the circumference of either fluid-filled wheel. Hence, the need for the rotational synchronization circuitry, which is illustrated in the patent. This necessity is primarily attributable to the difficulty of manufacturing conformable tires to high (micron-level) circumferential thickness tolerances (usually as a result of a slight off-axis translation between the inner and outer tire surfaces during the manufacture, i.e., liquid casting, of the tires). It should be obvious from the drawing below that any nonzero axial displacement between the two surfaces naturally leads to a sinusoidal variation of tire circumferential thickness with angular position.

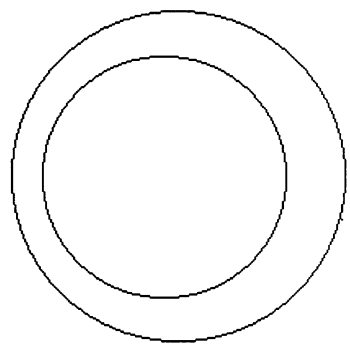

Fig. 1

Additionally, a nonuniform and unpredictable shrinkage of the tire material during the casting process may further reduce the uniformity of the circumferential thickness of the tires. Also, because it is difficult to match the circumferences (via relative liquid inflation pressures) of the two tires exactly, the wheels, which are held in constant contact essentially without slippage, inevitably move slowly out of relative phase after many rotations. Thus, although two arbitrary points along either tire circumference may be precisely aligned at the point of nip contact at a given moment, after a large number of wheel rotations, those two angular positions (and the corresponding circumferential thicknesses at the point of nip contact) will slowly diverge, leading to a slow departure from the optimal calibration taken at an instantaneous arbitrary phase the last time that the wheels were standardized offsheet. The greater the circumferential (i.e., diameter) mismatch between the tires and the greater the rotational rate of the tires, the more quickly a new off-sheet calibration will be required to maintain measurement accuracy. These off-sheet standardizations are necessary because the velocities of ultrasound through the tire thickness and fluid paths are not identical and are unresolved.

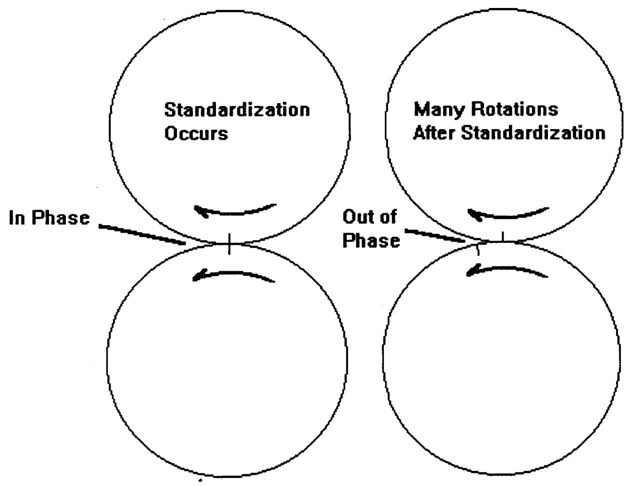

Fig. 2

Recent refinements of the measurement method alleviate the need for wheel phase alignment in that the components of ultrasonic transit time through the thicknesses of the two tires are now accounted for identically and may now be extracted from the measurement of every velocity measurement of ultrasound through the paper, dramatically improving the accuracy, precision and robustness of both caliper and transit time measurements.

Temperature and Calibration Issues

The patent describes the use of a solid delay line (see Fig. 6) attached to the emitting transducer in order to estimate ultrasonic velocity through the fluid, which varies with changing fluid temperatures. It is necessary to develop a calibration curve in the laboratory that relates ultrasonic velocity through the delay line material versus the actual velocity of ultrasound through the fluid that surrounds it. This is done by making repeated offsheet measurements in the laboratory at two axial wheel displacements after the wheels and fluid that they contain are heated and then slowly allowed to cool through the entire temperature range that may be expected during actual operation of the instrument. A (normally small) calibration error may be introduced during this calibration process. Also, if the thermodynamic equilibrium of the rotating fluid-filled wheels changes such that the fluid temperature (and, hence, the velocity of ultrasound through the fluid) changes, then the velocity of ultrasound within the solid delay line material may be expected to lag the velocity through fluid somewhat, leading to small transient inaccuracies in the ultrasonic fluid velocity calculations.

Recent refinements in the measurement method alleviate both the need for the cool-down calibration and any error due to lagging delay line temperature changes relative to the actual fluid temperature changes. Also, the ultrasonic fluid velocities within either tire are taken from a velocity sampling from only one of the tires. Now, the ultrasonic velocity through fluid within both tires may be measured directly and independently, further increasing the accuracy of the measurement of ultrasound through the paper.

Robustness and Sensitivity

Finally, the t_2 pulse must travel a torturous route to reach the receiving transducer. This long and complicated path, which involves several reflections off of various material boundaries and several reversals in propogation direction, necessitates that t_2 will have lost a great deal of energy by the time it reaches the receiving transducer and will therefore be somewhat degraded by electromagnetic and acoustic noise. This is especially true for highly attenuative specimens that further weaken the ultrasonic signal strength of signals that pass through them. This attenuation/noise factor generally leads to small errors in the calculation of ultrasonic transit time of t_2 relative to t_1 via the crosscorrelation integral, even though that calculation is inherently resistant to these inaccuracies.

Recent refinements have reduced the indirectness of the propogation paths of ultrasound through the media through which the ultrasonic pulses must travel, thereby increasing the accuracy and robustness of the system. The refinements mentioned above, in conjunction with a reduction in the diameter of the advancing ultrasonic wavefront, have improved the accuracy and precision of the instrument to such a degree that it is now possible to reliably measure highly localized areas of paper relating to the small (formation level) features of paper. In fact, it is now possible to simultaneously measure both the transit time of ultrasound through the paper and the caliper of the paper through identically aligned 1/2" round specimen areas of the moving web without the need to average subsequent measurements to achieve optimal precision. On a typical linerboard sample whose ultrasonic transit time averages around 500 nanoseconds, the measurement is precise to approximately 5 nanoseconds (1%) during wheel rotation. The caliper component (a more complicated measurement challenge) of a measurement set has been reduced to approximately 5% with expectation of further decrease.

Measurable Features of Paper

A 20-ft CD strip (see Fig. 7) was spliced as a belt and transported through the nip between the two wheels and was allowed to make two complete circuits through the nip as instantaneous caliper/transit time/velocity measurement sets were generated at a rate determined by a free-running (approximately 50 Hz) clock. A comparison between the two measurement series over a single short representative length of the strip (chosen because the free-running measurement clock happened to be in reasonable spatial synchronization at those corresponding time intervals) reveals a striking repeatability through a wide range of actual point-to-point paper variation (see Fig. 8). These variations are undoubtedly closely related to localized basis weight variations (i.e., formation features) in the paper structure. This mapping may be expected to include detailed information related to the often observed banding of the sheet through the CD width of the web due to nonuniform fiber slurry deposition onto the wire, stock jump, and other turbulent sheet forming factors. It is undoubtedly closely related to the formation of the sheet, and unlike optical methods of measuring sheet formation, appears to measure 'structural,' as opposed to optical, formation features.

However, the purpose of the ZD wheels is primarily intended for on-line measurements through the MD at high transport speeds rather than slow off-line measurements. The accuracy and precision of the measurement are generally reduced a few percent during very high-speed transport due to mechanical vibrational factors, although the present instrument accounts for the majority of them intrinsically. Still, the measurement accuracy should not be substantially degraded and should remain a strong indicator of both formation features and the CD character of the sheet even while operating at on-line transport speeds and conditions. Even though each measurement set (i.e., caliper/transit time/velocity) will be widely spaced from the previous measurement set (i.e., caliper/transit time/velocity), a group of several contiguous measurements should still provide formation level information if their standard deviation or coefficient of variation is calculated. Even though seperate measurements are widely spaced along the MD, they will still

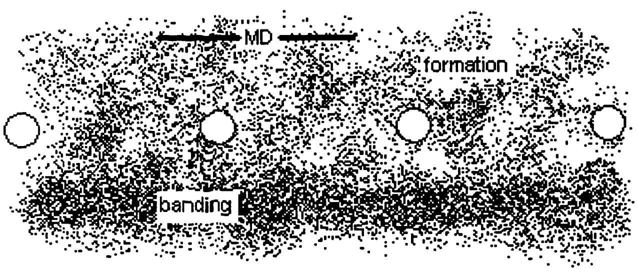

Fig. 3

be closely spaced over short scan intervals along the CD as the scanning platform to which the instrument is attached scans at a constant and relatively slow velocity. This is because the measurement repetition rate is fast enough to keep up with the scanning velocity and produce reasonably numerous populations of measurements over short CD intervals.

The refined ZD instrument has been designed to operate over a wide range of web transport speeds, making it suitable for a variety of measurement functions from relatively slow or even static laboratory speeds useful for characterizing CD strips and MD reels of paper at high spatial resolution up to high-speed on-line testing in harsh environments.

It is important to note that a number of papermaking and raw material factors influence the resultant elastic stiffness character of paper. Basis weight/formation, caliper, wet pressing, calendering, refining, chemical additives, draws/wet straining, recycle content, and other factors secretly conspire to produce a certain elastic stiffness character. Theoretical and empirical relationships relating these variables and others are somewhat useful in predicting ring crush, STFI, box performance, etc. These relationships are useful in a way that is analogous to knowing how the steering wheel will respond while driving a car. However, it is the visual perception of the position of the car relative to the road that is ultimately the most important factor in a successful drive. This instrument and other on-line measurement technologies allow rapid feedback in response to changes (intentional or unintentional, observed or unobserved, controllable or uncontrollable, or 'seemingly' uncontrollable) in the papermaking process. It will undoubtedly be those individuals who have a good general understanding of the nature of stiffness parameters in paper and are intimately familiar with the papermaking process, the nature of raw material entering the process, and the quality of the final product (as judged primarily by customers) who will be in the best position to exploit, through the benefit of their expertise and experience, the results of these on-line fast measurement technologies.

The present fastest measurement repetition rate with our current digital signal processing hardware is approximately 50 measurements per second, a rate that should go somewhat higher with planned calculation efficiency enhancements. However, the measurement rate is ultimately limited only by the time it takes for all of the echoes bouncing around as a result of the last ultrasonic pulse emission to die out to negligible levels. With optimally minimized ultrasonic propogation path lengths, that rate can go all the way up to several hundred measurements per second. As new digital signal processing technology becomes available, the allowable measurement rate will ultimately converge on this maximum rate.

ACKNOWLEDGEMENTS

This work has been supported by the U.S. Department of Energy (Contract No. DE-FC02-95CE41156) and by the Member Companies of IPST.

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US005493911A

United States Patent [19]

Hall et al.

[11] Patent Number: 5,493,911

[45] Date of Patent: Feb. 27, 1996

[54] **SYSTEM FOR MEASURING THE ULTRASONIC VELOCITY IN THE THICKNESS DIRECTION OF MOVING WEBS WITHOUT ERRORS DUE TO DELAYS IN THE ONSET OF DIGITIZATION**

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[73] Assignee: **Institute of Paper Science and Technology, Inc.**, Atlanta, Ga.

[21] Appl. No.: **380,379**

[22] Filed: **Jan. 30, 1995**

Related U.S. Application Data

[63] Continuation of Ser. No. 971,048, Nov. 30, 1992, abandoned.

[51] **Int. Cl.**[6] **G01N 29/18**

[52] **U.S. Cl.** **73/597**; 73/598; 73/639; 73/159

[58] **Field of Search** 73/597, 598, 159, 73/602, 627, 628, 629, 639, 644, 635

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Primary Examiner—Hezron E. Williams
Assistant Examiner—Nashmiya Ashraf
Attorney, Agent, or Firm—Fitch, Even, Tabin & Flannery

[57] **ABSTRACT**

A system for relatively accurately measuring the velocity and time of flight of ultrasonic signals in the thickness direction through moving web-like materials, such as paper, paperboard and the like, includes a pair of ultrasonic transducers disposed on opposing sides of the moving web-like material. The ultrasonic transducers are disposed in fluid-filled wheels to provide acoustical coupling between the transducers and the web-like material. In order to eliminate errors, known as trigger jitter, inherent in systems used to digitize ultrasonic signals for manipulation by a digital computer, a pulse echo box is provided to enable the capture of a reflected ultrasonic signal in addition to the ultrasonic signal transmitted through the web. By cross-correlating the transmitted and reflected ultrasonic signals in the same sample period, the error associated with trigger jitter is eliminated.

8 Claims, 8 Drawing Sheets

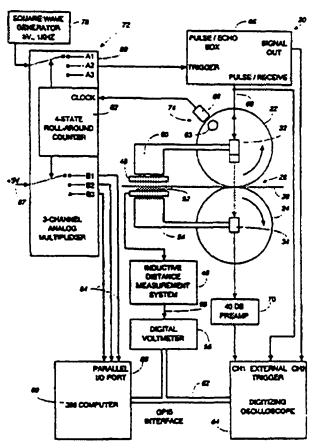


Fig. 4

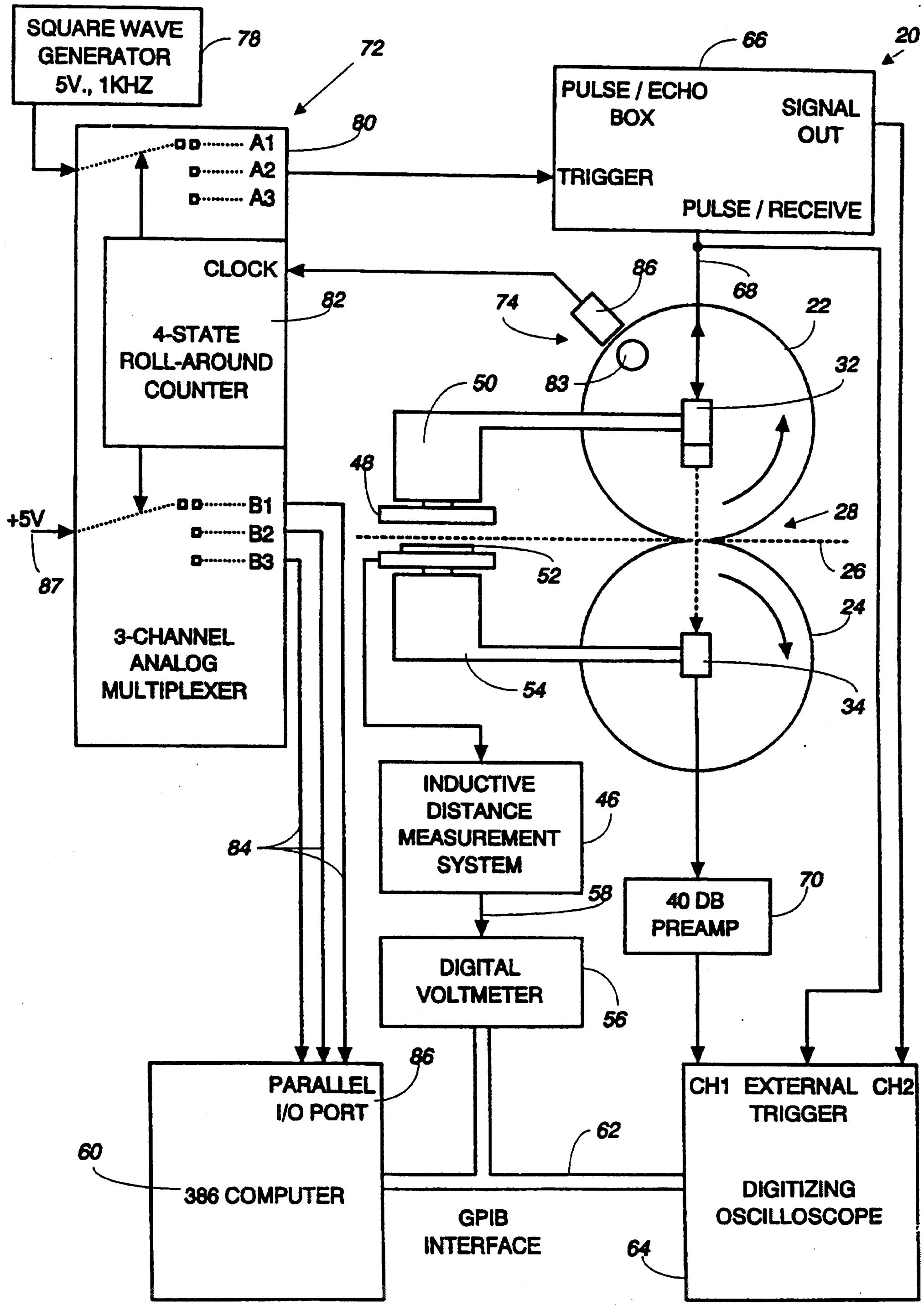
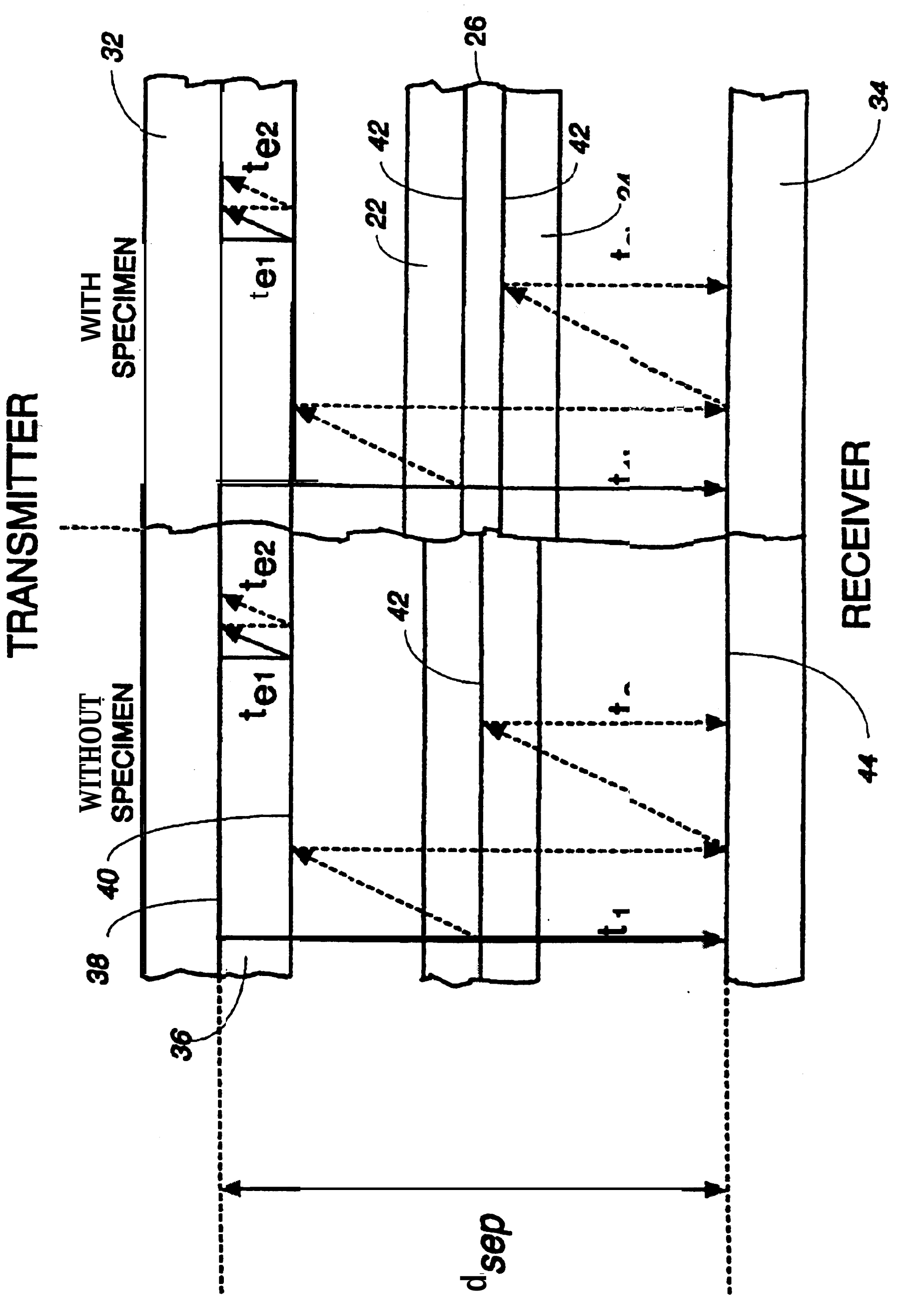
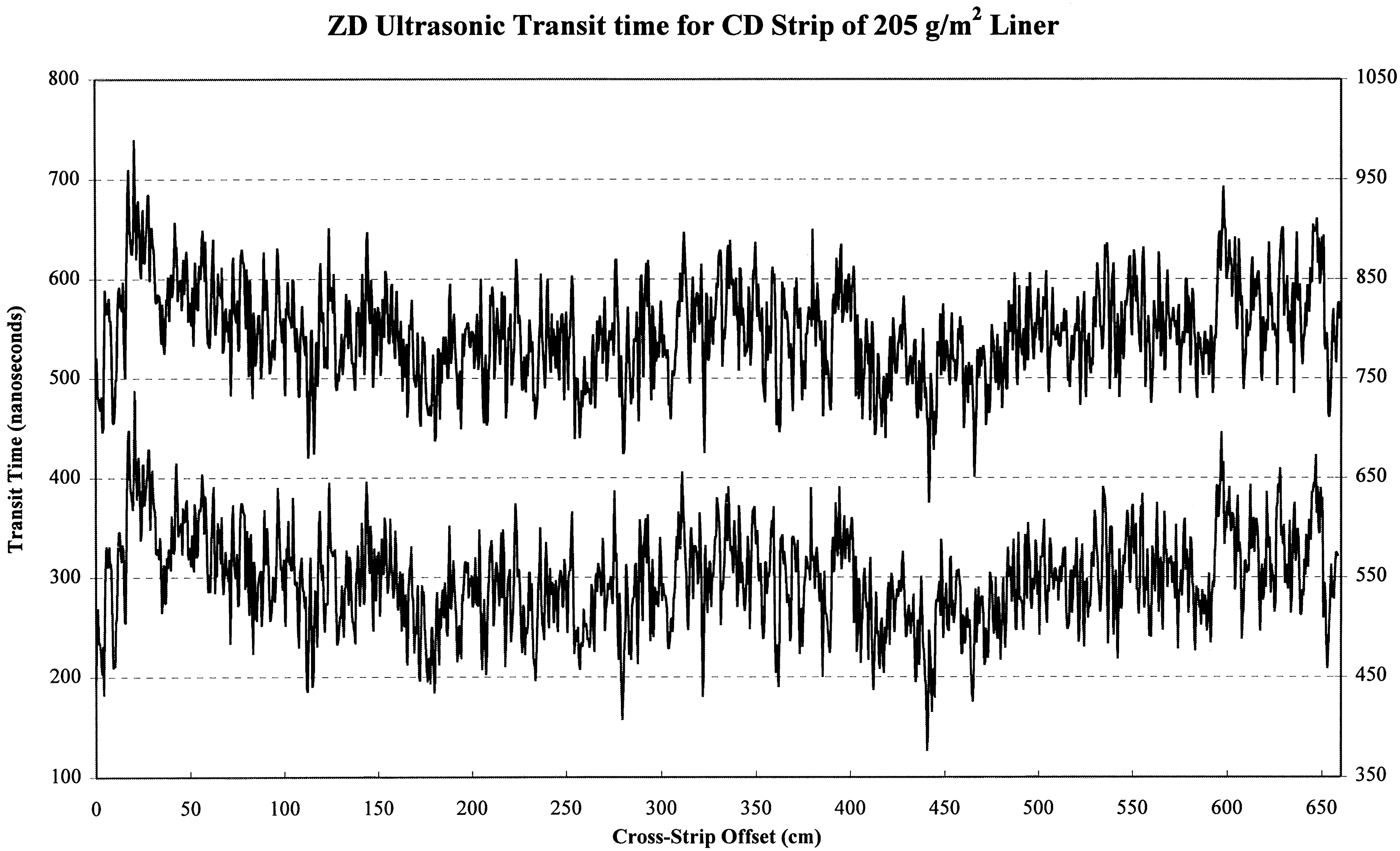

SQUARE WAVE GENERATOR 5V., 1KHZ
78
72
80
A1
A2
A3
CLOCK
82
4-STATE ROLL-AROUND COUNTER
B1
B2
B3
+5V
87
3-CHANNEL ANALOG MULTIPLEXER
84
PULSE / ECHO BOX
SIGNAL OUT
TRIGGER
PULSE / RECEIVE
66
20
86
68
74
22
83
32
50
48
28
26
52
24
54
34
INDUCTIVE DISTANCE MEASUREMENT SYSTEM
46
58
DIGITAL VOLTMETER
56
40 DB PREAMP
70
PARALLEL I/O PORT
86
386 COMPUTER
60
62
GPIB INTERFACE
CH1 EXTERNAL CH2 TRIGGER
DIGITIZING OSCILLOSCOPE
64

Fig. 5



22 - Upper Tire
24 - Lower Tire
26 - Specimen
32 - Transmitting Transducer
34 - Receiving Transducer
36 - Delay Line
38 - Transmitting Transducer Surface
40 - Delay Line Surface
42 - Offsheet Nip
44 - Receiving Transducer Surface

Fig. 6



ZD Ultrasonic Transit time for CD Strip of 205 g/m2 Liner
Transit Time (nanoseconds)
800
700
600
500
400
300
200
100
1050
950
850
750
650
550
450
350
0
50
100
150
200
250
300
350
400
450
500
550
600
650
Cross-Strip Offset (cm)

Fig. 7

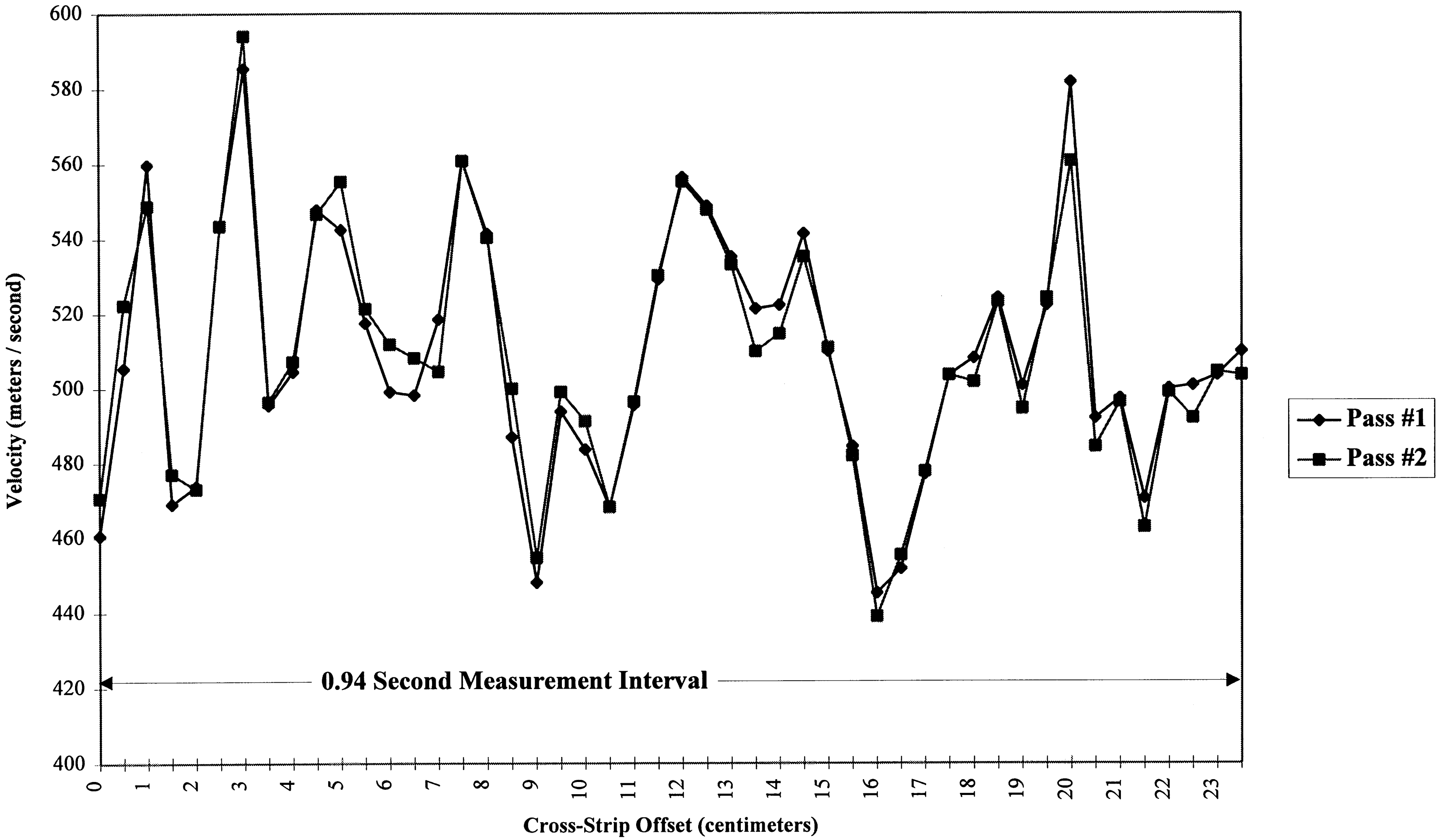

Velocity (meters / second)
600
580
560
540
520
500
480
460
440
420
400
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Cross-Strip Offset (centimeters)
0.94 Second Measurement Interval
Pass #1
Pass #2

Fig. 8